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Quantum-state-preserving optical pulse reshaping and multiplexing by four-wave mixing in a fiber

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Abstract: Nondegenerate four-wave mixing driven by two pulsed pumps transfers the quantum state of an input signal pulse to an output idler pulse, which is a frequency-translated and reshaped version of the signal. By varying the pump shapes appropriately, one can connect signal and idler pulses with arbitrary durations and shapes. This process enables a variety of functions required by quantum information networks.

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1. Summary

A key requirement of quantum information networks is the ability to transport quantum states between nodes [1, 2]. These nodes (material-based quantum memories with resonance wavelengths in the range 300–800 nm) could be nearby (in the same device) or distant (linked by optical fibers with low-loss windows centered on 1310 or 1550 nm). Their resonance wavelengths could be the same, or similar, or could differ significantly. Furthermore, the durations and shapes of pulses emitted by quantum memories differ significantly from the short bell-shaped pulses favored by communication systems. To optimize the transmission of quantum information, and the exchange of information between different channels, the ability to frequency translate (FT) and reshape optical pulses, while preserving their quantum states, is essential.

Quantum-state-preserving FT is enabled by three-wave mixing (TWM) in a crystal [1, 3]. In this process, a strong pump wave (p) couples weak signal (s) and idler (r) waves ($\pi_s \longleftrightarrow \pi_p + \pi_r$, where π_j represents a photon with frequency ω_j). Recently, it was shown theoretically that TWM, in conjunction with spectral phase modulation and propagation [4], or complicated dispersion engineering [5], can connect pulses with disparate durations.

Quantum-state-preserving FT is also enabled by four-wave mixing (FWM) in a fiber [6, 7]. In the nondegenerate FWM process called Bragg scattering (BS), two pumps (p and q) couple the signal and idler ($\pi_s + \pi_p \longleftrightarrow \pi_q + \pi_r$). BS has been used in conventional communication experiments to provide tunable FT and multiplexing. It also has the ability to reshape pulses arbitrarily, without additional processing or complicated dispersion engineering.

BS is governed by the coupled-mode equations (CMEs)

$$(\partial_z + \beta_r \partial_t) a_r(z, t) = i \gamma_{pq}(z, t) a_s(z, t), \quad (\partial_z + \beta_s \partial_t) a_s(z, t) = i \gamma_{pq}^*(z, t) a_r(z, t), \quad (1)$$

where a_r and a_s are the annihilation operators of the idler and signal, respectively, β_r and β_s are the group slownesses, $\gamma_{pq}(t, z) = \gamma A_p(t - \beta_s z) A_q^*(t - \beta_r z)$ is the pump-induced coupling function, γ is proportional to the Kerr coefficient and A_j is a pump amplitude [6]. Pump p co-propagates with the signal, whereas pump q co-propagates with the idler [7]. We determined the Green functions associated with the CMEs analytically, and performed their Schmidt decompositions numerically. The Schmidt modes (temporal eigenfunctions) are the optimal input and output pulse shapes, and are related to the pump shapes. The Schmidt coefficients (eigenvalues) are intermodal conversion efficiencies.

The signal-to-idler Green function G_{rs} was decomposed numerically for a fiber that was long enough to allow a complete pump–signal interaction. In Fig. 1(a), the first and second Schmidt coefficients ($|\rho_1|^2$ and $|\rho_2|^2$) are plotted as functions of the interaction strength [$\tilde{\gamma} = \gamma/(\beta_r - \beta_s)$]. In the low-strength regime, the first coefficient (conversion efficiency) $|\rho_1|^2 \approx \tilde{\gamma}^2$. In the high-strength regime, $|\rho_1|^2$ tends monotonically to 1 as $\tilde{\gamma}$ increases, so complete conversion is possible. For efficiencies as high as 0.70, the value of the second Schmidt coefficient is no larger than 0.01, so the Green function is nearly separable: The first (target) Schmidt mode is converted with reasonable efficiency, whereas the other modes are unaffected. For higher efficiencies, the second coefficient increases rapidly and the potential exists

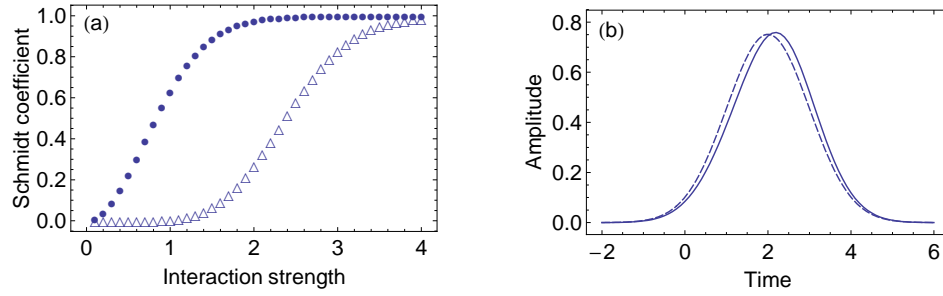


Fig. 1. (a) Schmidt coefficients ($|\rho_n|^2$) plotted as functions of the strength parameter ($\tilde{\gamma}$). The solid circles denote $|\rho_1|^2$ and the hollow triangles denote $|\rho_2|^2$. (b) Lowest-order Schmidt mode (solid curve) and (common) pump shape (dashed curve) plotted as functions of time (t/τ) for the strength parameter $\tilde{\gamma} = 0.834$.

for intermodal crosstalk. The first Schmidt mode of G_{rs} is displayed in Fig. 1(b) for the case in which $\tilde{\gamma} = 0.834$. This strength parameter corresponds to a conversion efficiency of 50%, which is suitable for entanglement generation or Hong–Ou–Mandel (HOM) interference. The pumps are identical Gaussians with root-mean-square duration τ and the (common) Schmidt mode differs only slightly from a Gaussian, as predicted by theory.

The first pair of Schmidt modes of G_{rs} is displayed in Fig. 2 for the case in which $\tilde{\gamma} = 1.544$. This strength parameter corresponds to a conversion efficiency of 90%, which is high enough for reliable quantum FT or entanglement swapping. Pumps p and q are zeroth- and first-order Hermite–Gauss functions, respectively, so the wavepacket is reshaped. The Schmidt modes are distorted Hermite–Gauss functions, as predicted by theory.

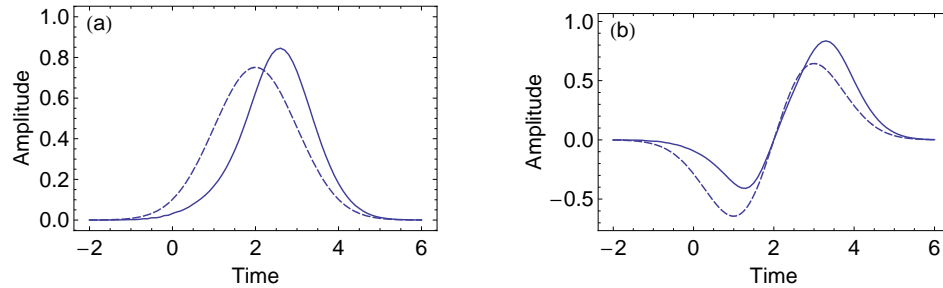


Fig. 2. Lowest-order (a) signal and (b) idler Schmidt modes (solid curves) and pump shapes (dashed curves) plotted as functions of time (t/τ) for the strength parameter $\tilde{\gamma} = 1.544$.

In summary, BS driven by pulsed pumps was studied in detail. The Green functions and Schmidt decompositions associated with this FT process were determined for arbitrary conversion efficiencies. BS enables the generation of entanglement, or HOM interference, between photons with different carrier frequencies and wavepackets, and photon FT, or entanglement swapping, with simultaneous wavepacket reshaping that is limited only by the available pump shapes (waveforms). Since arbitrary pump-waveform generation is possible [8], the future of FT by BS looks bright.

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